BaBar and Other ***B***eautiful Things

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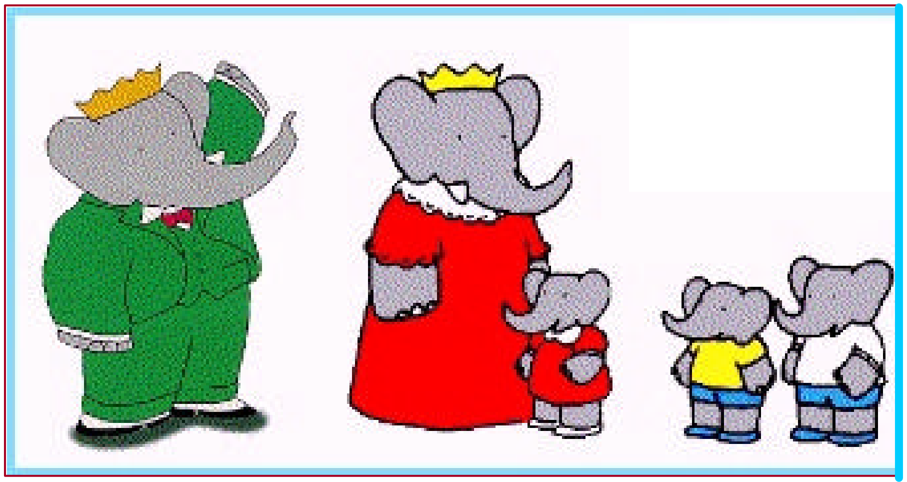


BaBar TM Laurent de Brunhoff

Outline

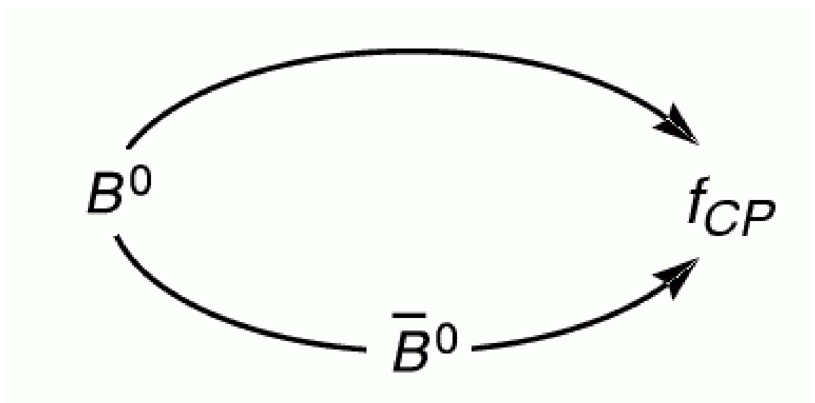
- Why is heavy-quark physics interesting?
- The BaBar experiment: a quintessential modern *B* factory
- Measurements and what they tell us:
  - The simplest processes: semileptonic and leptonic decays and the magnitudes of CKM elements
  - Rare *B* decays, penguins, and searches for direct *CP* violation
  - Mixing in the neutral *B* meson system
  - Time-dependent *CP* asymmetries from the interference between mixing and decay
- Conclusions and prospects

Why Is Heavy Quark Physics Interesting?

1. What is the origin of *CP* violation?

- SM predicts very large *CP* asymmetries in the *B* meson system arising from the interference between B^0-$\overline{B}^0$ mixing and decay

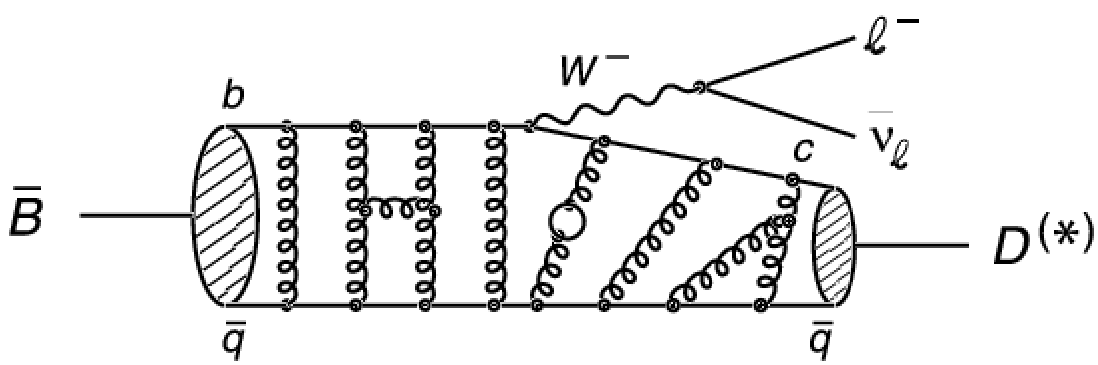
- The currently operating *B* factories are performing a comprehensive set of measurements to determine whether *CP* asymmetries in the *B* system are consistent with SM predictions



Why Is Heavy Quark Physics Interesting? (2)

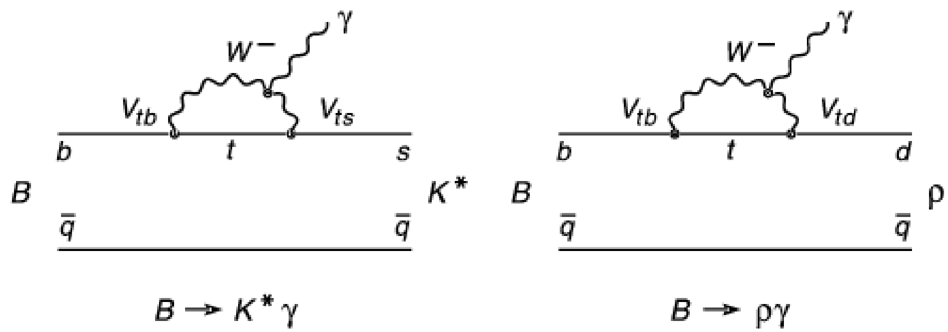
2. Measure the **rates** for relatively simple processes to extract the **magnitudes** of the CKM matrix elements.
   - In the SM, semileptonic decays are simple tree diagrams with no interference effects.
     - $|V_{cb}|$ and $|V_{ub}|$ are determined from semileptonic decays, while $|V_{td}|$ and $|V_{ts}|$ can be determined from B^0-$\overline{B}^0$ and B_s-$\overline{B}_s$ mixing and $b \to t \to s(d)$ penguins
     - Measurement of the magnitude of a CKM element requires significant theoretical input based on an understanding of the decay dynamics

$$\boxed{B(M_{Q\overline{q}} \to X_{q'\overline{q}} l n) = g_{\text{theory}} \, |V_{q'Q}|^2 \, t_M}$$



Why Is Heavy Quark Physics Interesting? (3)

3. Search for the effects of **new physics** in a variety of sensitive rare processes with loops.
   – Electroweak- and hadronic-penguin decays; D^0-$\bar{D}^0$ mixing, etc.

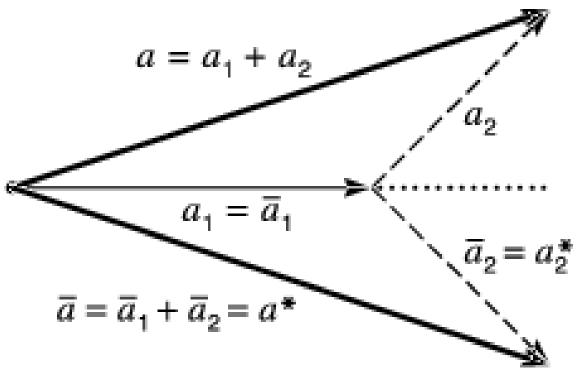


4. Understand the complicated interplay between the underlying **weak** processes and **strong** interaction effects
   – Measure and understand meson decay constants, semileptonic decay form factors, patterns of hadronic decays
   – Impressive theoretical developments: heavy-quark effective theory (HQET), lattice QCD calculations, etc.

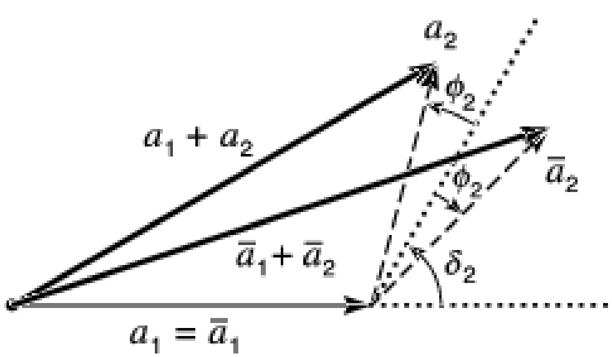
All of these goals are closely related!

Weak Phases and *CP* Violation

What conditions do we need to produce *CP* asymmetry?



(a)



(b)

CP Violating Phase (ϕ_2) without *CP* Asymmetry

$$a = a_1 + a_2 = |a_1| + |a_2|\, e^{if_2}$$

$$\bar{a} = |a_1| + |a_2|\, e^{-if_2}$$

$$\boxed{|a| = |\bar{a}|}$$

CP Violating Phase with *CP* Asymmetry

$$a = a_1 + a_2 = |a_1| + |a_2|\, e^{i(f_2 + d_2)}$$

$$\bar{a} = |a_1| + |a_2|\, e^{i(-f_2 + d_2)}$$

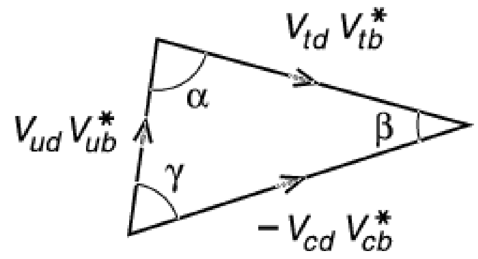
$$\boxed{|a| \neq |\bar{a}|}$$

➡ Need processes in which the *CP* conserving phase δ_2 is well understood!

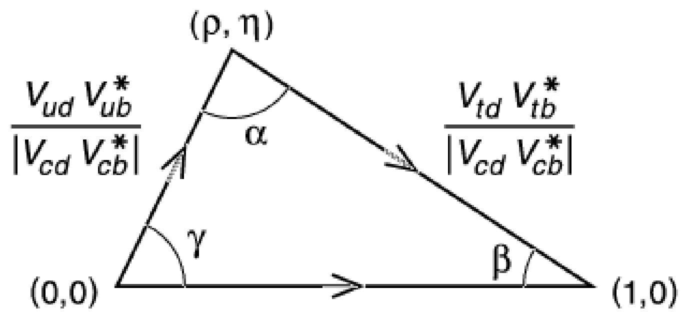
The CKM Matrix and Unitarity Triangle

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4).$$

- Unitarity + remove unphysical quark phases => 4 independent parameters in SM with 3 generations
- Wolfenstein: A, λ, η, ρ
- 6 unitarity triangles: all have same area ~ $J_{CP} = A^2\eta\lambda^6$, but the *CP* asymmetries aren't the same!
- Column 1 x (Column 3)* gives standard triangle; all sides $O(\lambda^3)$

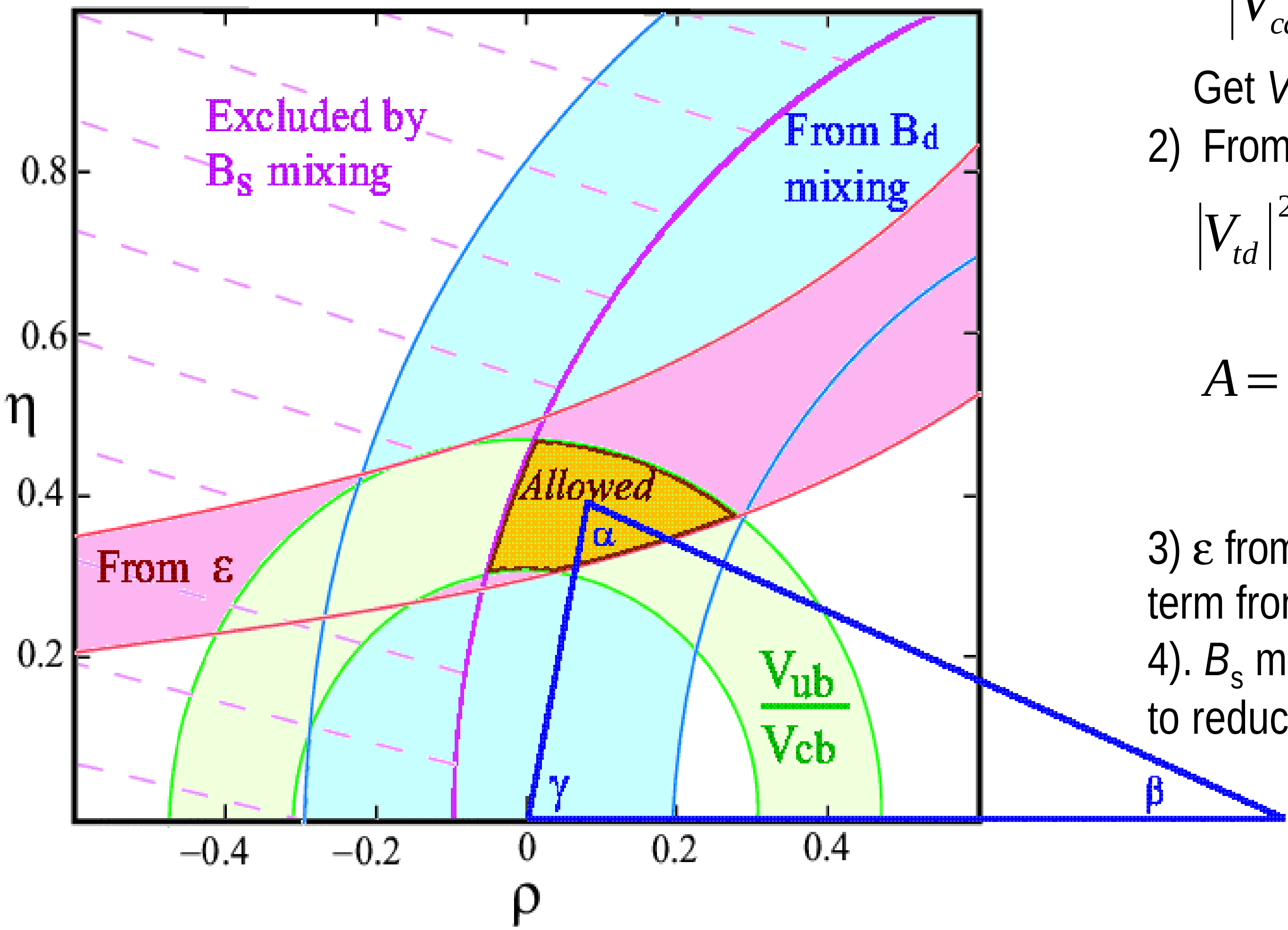


(a)



(b)

Constraints on the Unitarity Triangle



1) $\left|\frac{V_{ub}^*}{V_{cd}V_{cb}}\right| = \sqrt{r^2+h^2}$

Get V_{ub} from B –> X_u $l\nu$

2) From B^0 mixing:

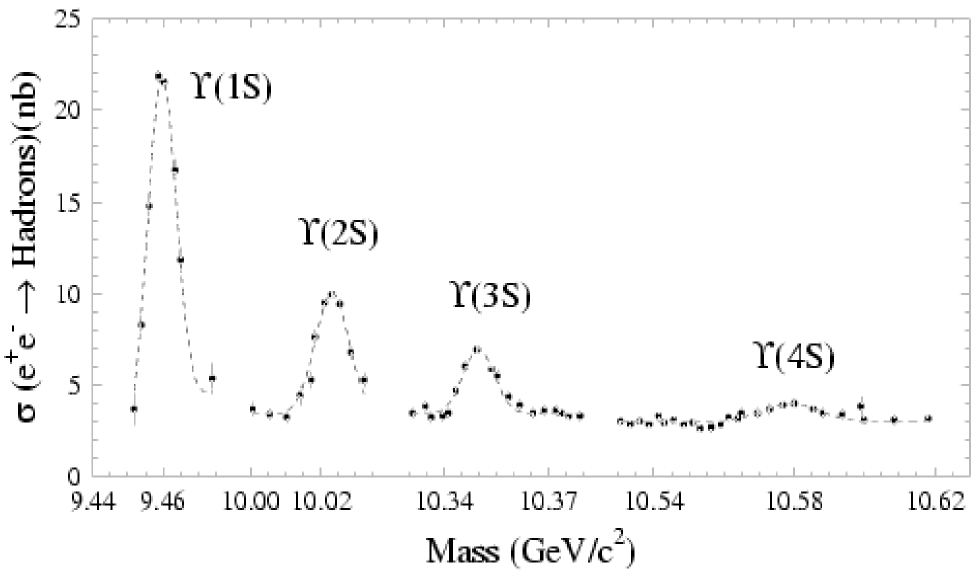
$$|V_{td}|^2 = A^2 l^2\left[(1-r^2)+h^2\right]$$

$$A = \left|\frac{V_{cb}}{V_{us}}\right|^2$$

3) ε from *CP* violation in *K* system (the term from intermediate $t\bar{t}$ states)

4). B_s mixing is useful because it allows to reduce the uncertainties on $|V_{td}|$

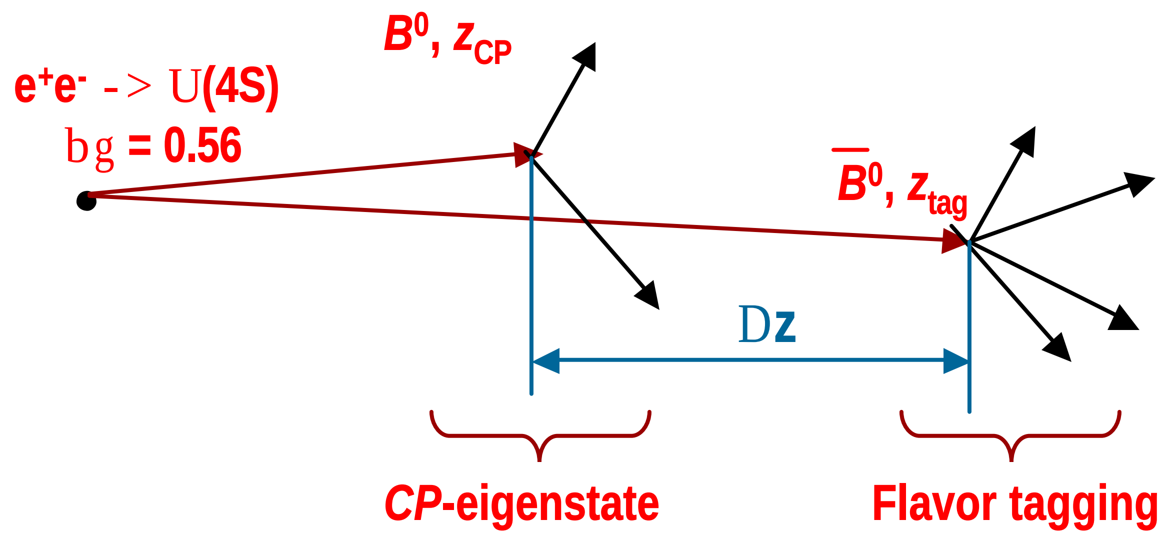
Producing *B* Mesons Using $e^+e^- \rightarrow \Upsilon(4S)$



- The $\Upsilon(4S)$ is just above threshold for producing $B\bar{B}$ pairs, so there is no accompanying particles
- $\sigma(e^+e^- \rightarrow \Upsilon(4S)) \sim 1.05$ nb
- $\sigma(e^+e^- \rightarrow q\bar{q}) \sim 3$ nb ($q = u,d,s$)

- $B\bar{B}$ production is a substantial fraction of the total hadronic cross section. Hadron machines have a much higher $b\bar{b}$ cross section (~ 50 μb), but this is a tiny fraction (~ 10^{-3}) of the total hadronic rate
- $p_B \sim 325$ MeV in $\Upsilon(4S)$ rest frame
- $B\bar{B}$ events have spherical topology (unlike $Z \rightarrow b\bar{b}$), while continuum events are jet-like

$B^0\overline{B}^0$ Production at Asymmetric-Energy Colliders



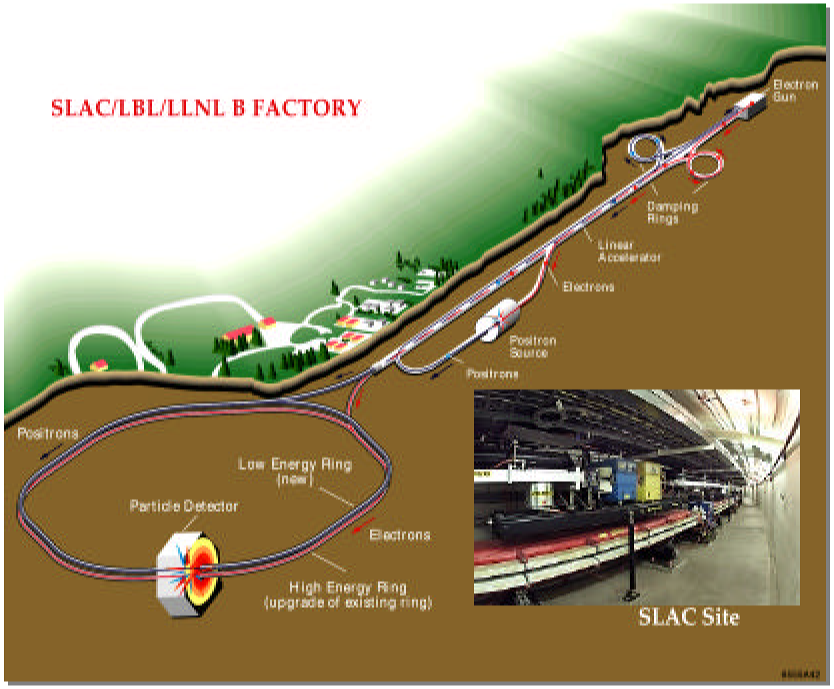
- The purpose of having asymmetric beam energies is to boost the $B^0\overline{B}^0$ system relative to the lab frame.

$$\Delta t = t_B = 1.6\, ps$$
$$\langle \Delta z \rangle = bg\, c\, t_B \approx 260\, mm$$

- By measuring Δz, we can follow time-dependent effects in *B* decays

e^+e^- storage ring at SLAC

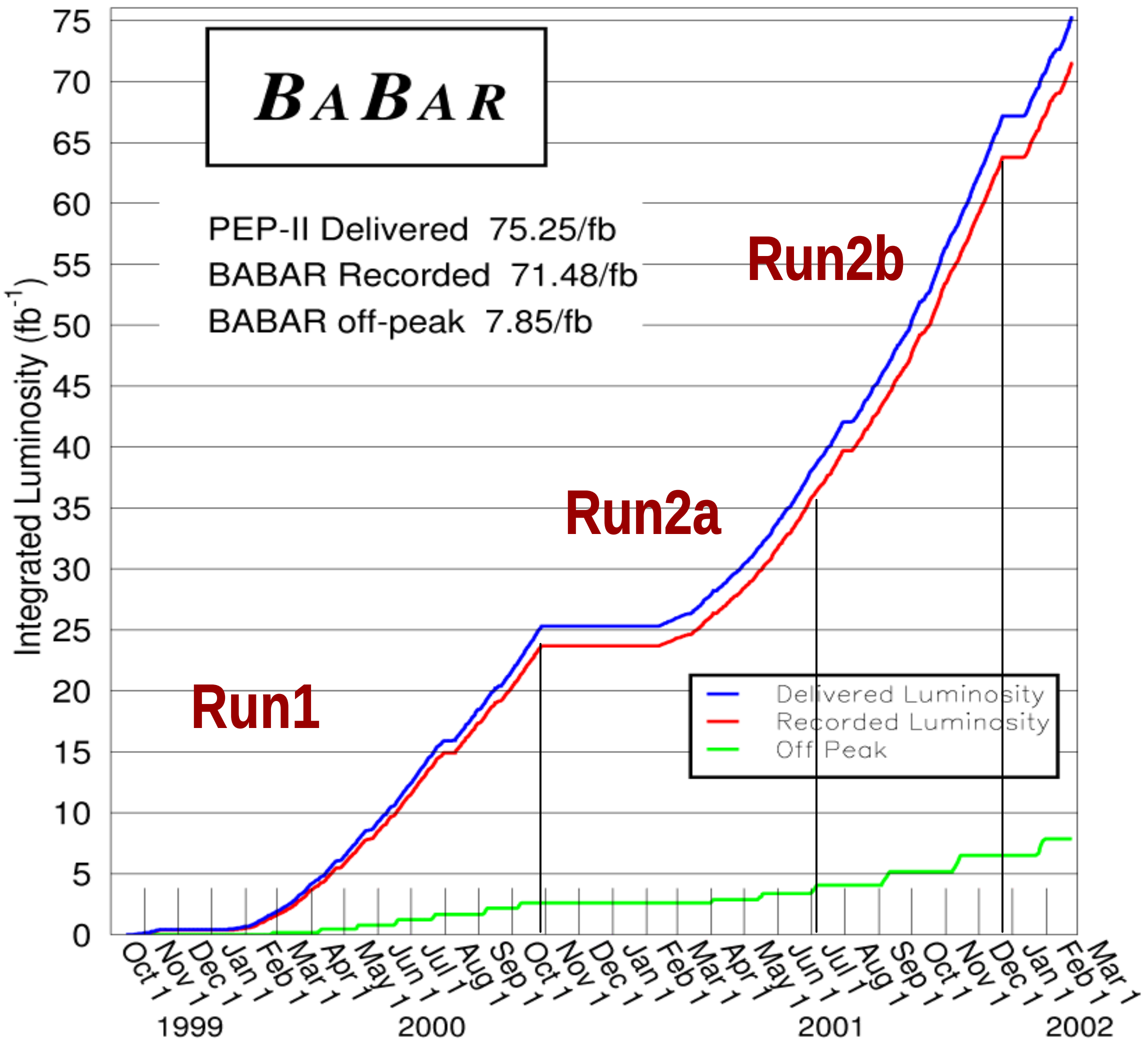
- The e^+e^- storage ring (PEP-II) at SLAC had to be updated to introduce the second ring, the low energy ring
  - The low energy ring was one of the most technically challenging storage rings ever created



- Electron ring finished in 1997
- Positron ring finished in 1998
- First collisions on July 23, 1998!

parameter	e^+ ring	e^- ring
energy (GeV)	3.1	9.0
total current (A)	2.14	0.9
top luminosity ($cm^{-2}s^{-1}$)	4.51×10^{33}	

PEP-II: Spectacular Performance!



Luminosity is defined as

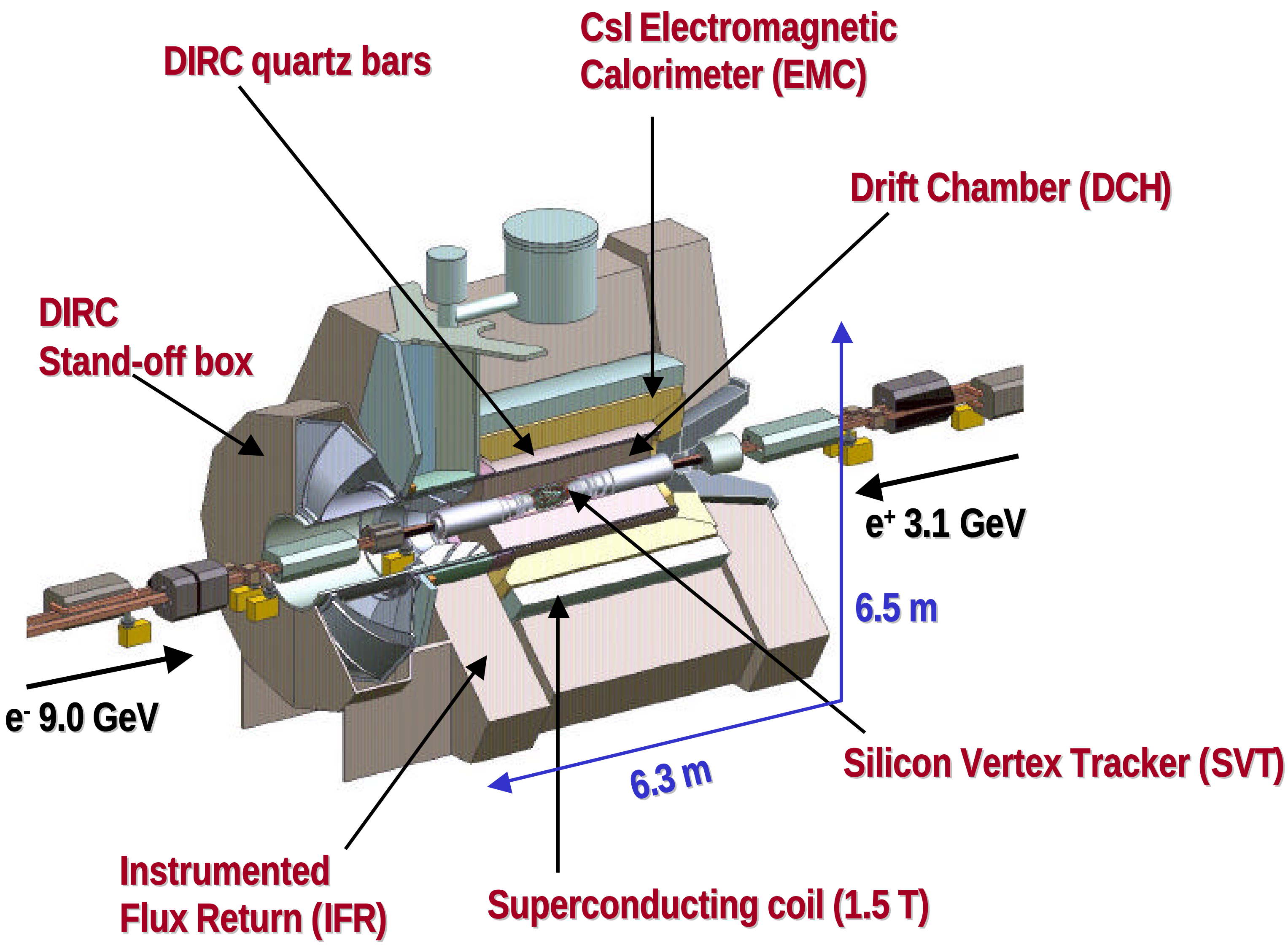
$$L = \frac{N_{e^+} \cdot N_{e^-} \cdot n_B \cdot f}{A}$$

where:

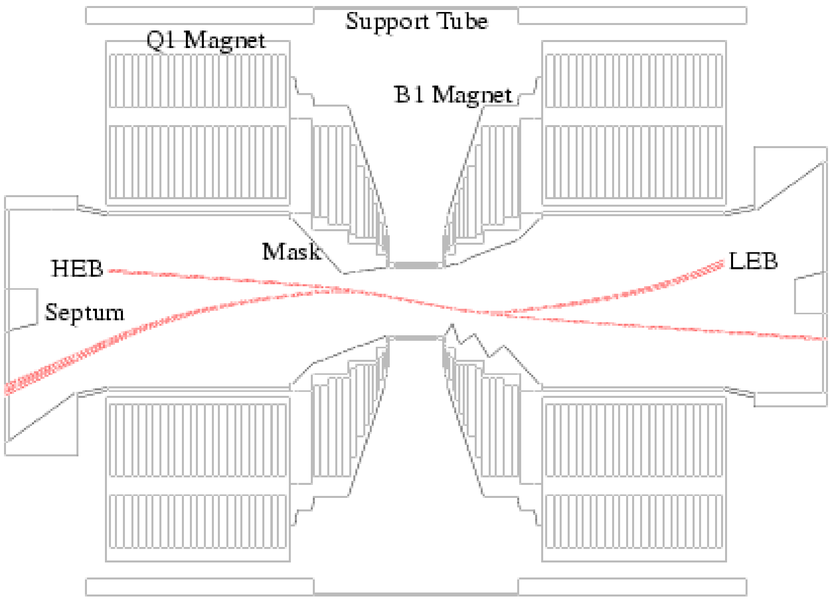
- N_{e-} is the number of e⁻/ bunch
- N_{e+} is the number of e⁺/ bunch
- n_B is the number of bunches
- f is the overlap frequency
- A is the area of the beam

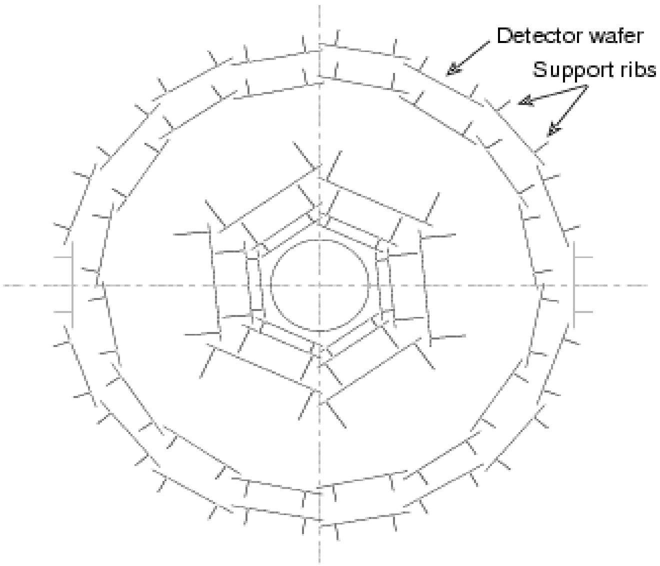
The recorded luminosity is a measure of how much data we get

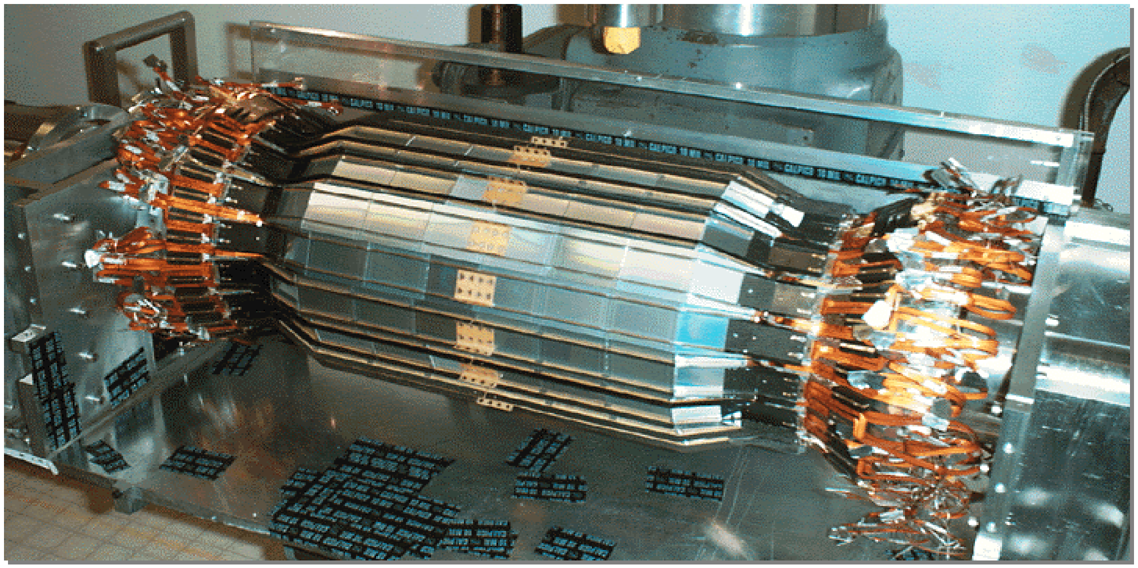
The BaBar Detector



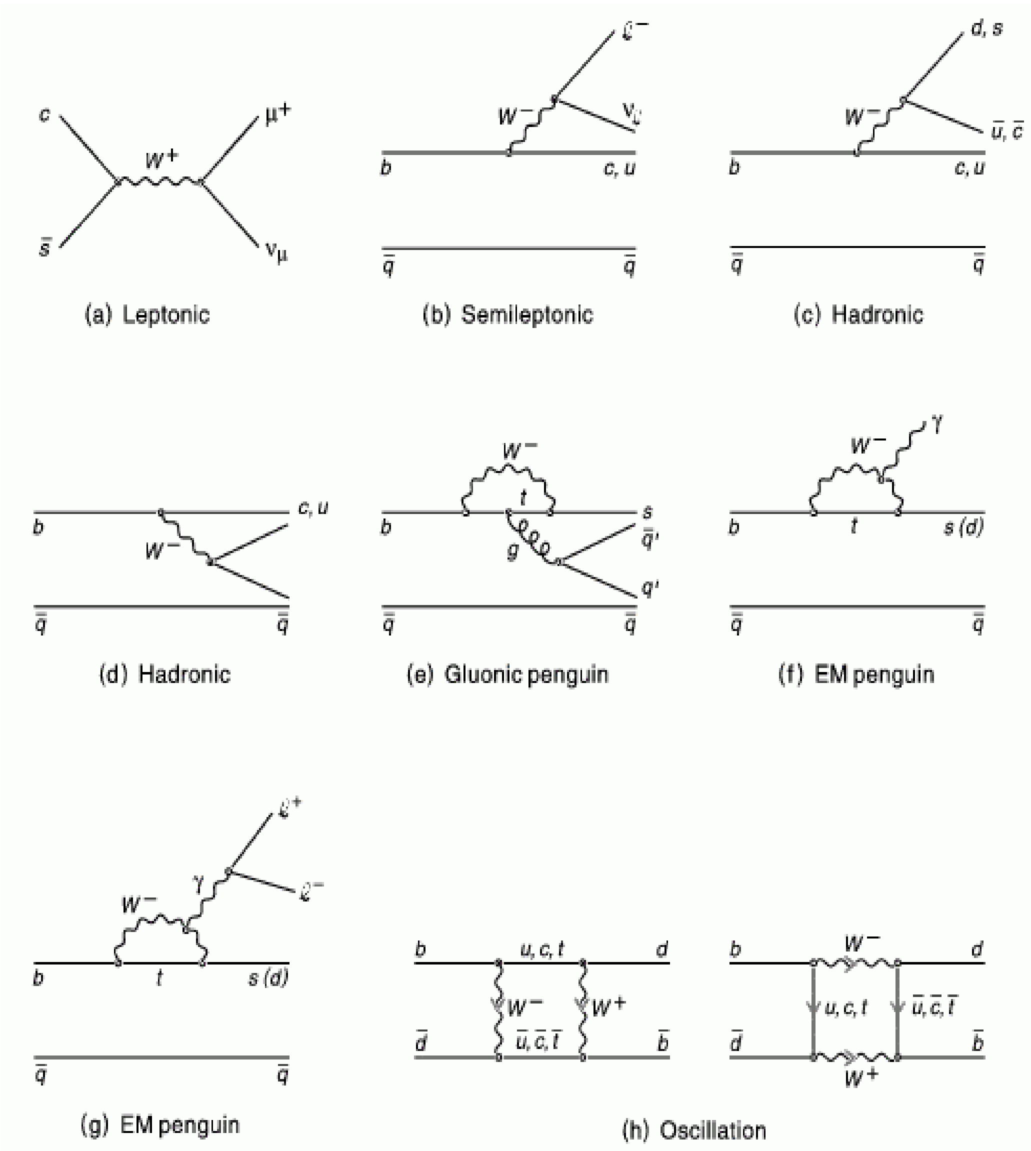
BaBar Silicon Vertex Tracker







Overview of *B* and *D* Decays and Oscillations

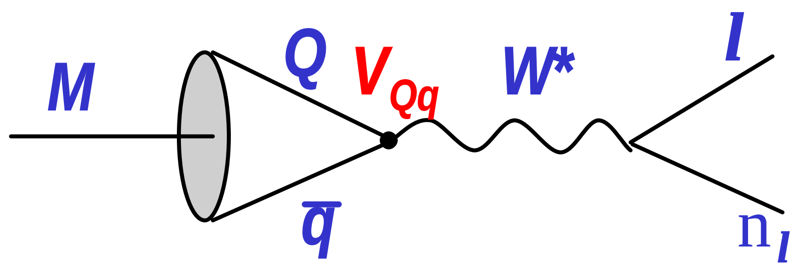


- In *B* decays, *b* –>*c* transitions are dominant, but even they are suppressed by $|V_{cb}|$ ~ 0.04
- Leptonic decay branching fractions are much lower for *B*, *D* than π, K because $\Gamma_{tot} \sim m_b^5$
- Largest *B* branching fraction:

  $B(B \to D^* l\nu) \sim 5\%$
- Hadronic decays: interference between internal and external *W* diagrams makes $\tau(D^+) >> \tau(D^0)$
- In hadronic *B* decays, the interference has opposite sign, but there is very little effect on the lifetimes: $\tau_{B+} \sim \tau_{B0}$.

Leptonic *B* decays

- Leptonic decays provide a clean way to probe the strong interactions that bind the quark-antiquark system in the initial state meson M

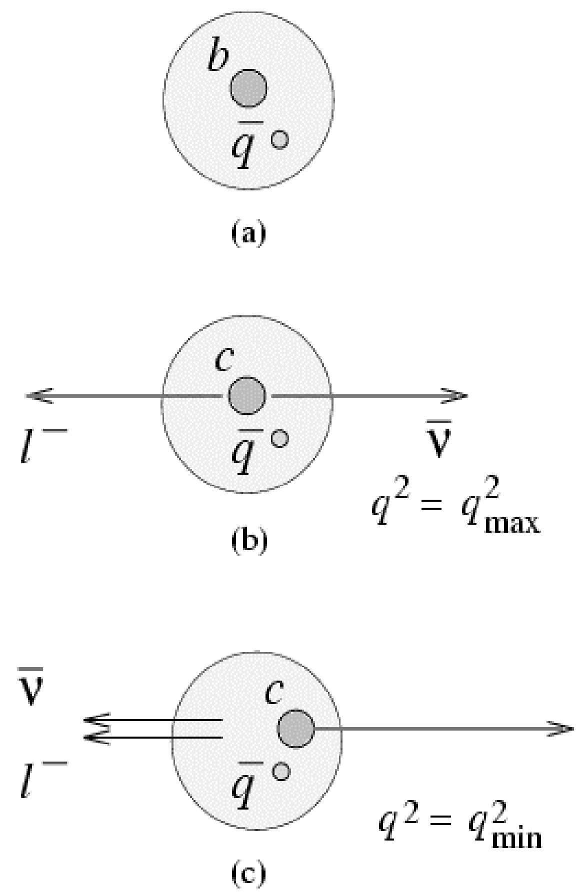


- Matrix element ~ (hadronic current x leptonic current), where hadronic current ~ decay constant
  - Decay const measures amplitude for Q and $\bar{q}$ to have zero separation
- Measuring decay constants is interesting because they can be compared with increasingly precise QCD calculations, and because they are needed to extract certain CKM matrix elements.

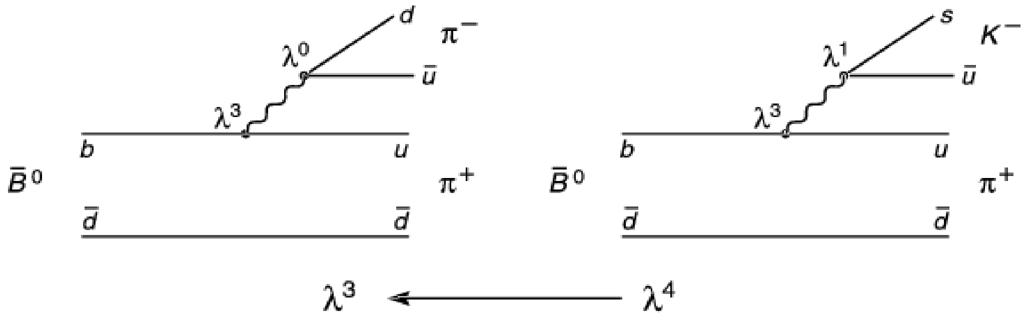
Semileptonic *B* decays

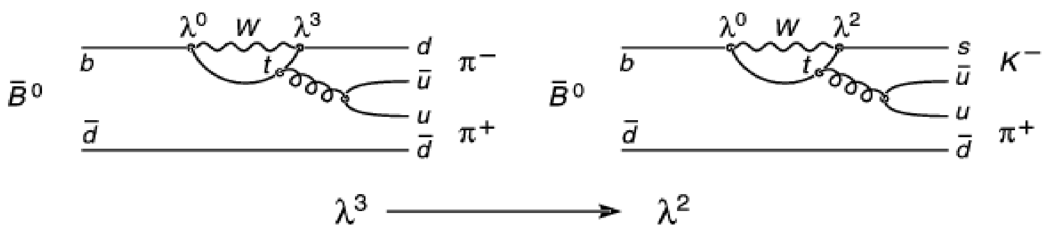
- Semileptonic decays are much simpler than hadronic decays. Strong interaction effects are important, but
  - They are isolated to the hadronic current
  - Their effect can be rigorously parametrized by form factors (Lorentz-invariant functions of $q^2 = (q_B - q_D)^2$)

- $b \rightarrow c l \nu$ processes are dominant and are much easier to understand than $b \rightarrow u l \nu$
  - Reliable theoretical normalization for $b \rightarrow c l \nu$ at zero recoil (Heavy-Quark Effective Theory)
  - Rates for $b \rightarrow u l \nu$ are much harder to predict, event at small recoil of the daughter hadron, and they have a much larger range of hadronic recoil velocities



Rare hadronic *B* decays

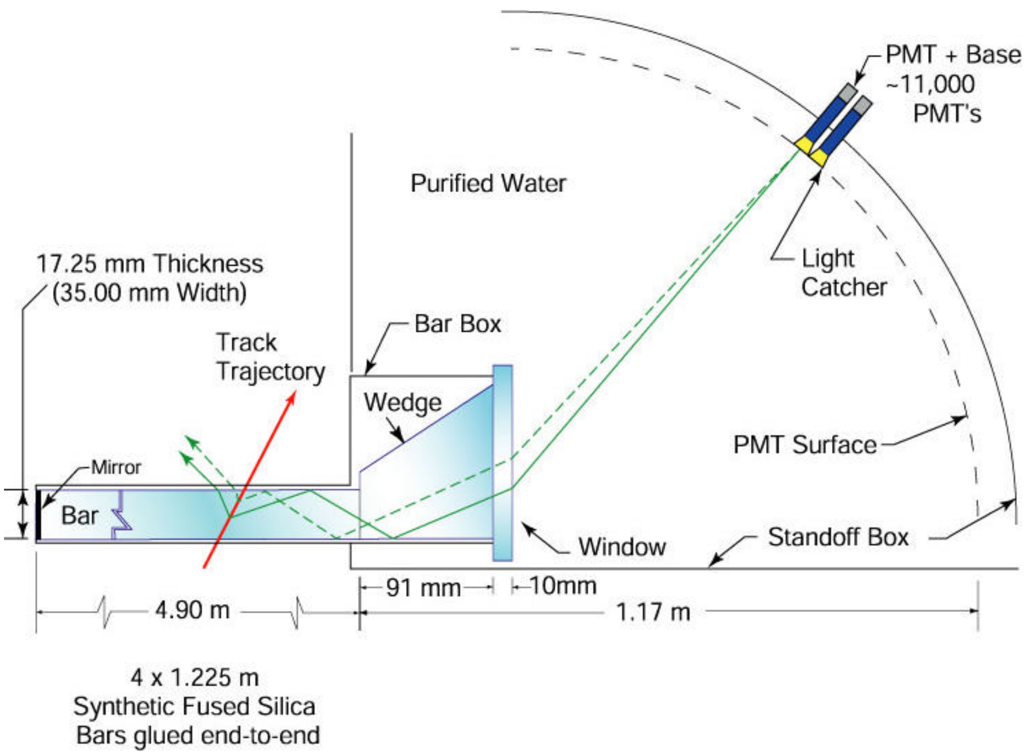




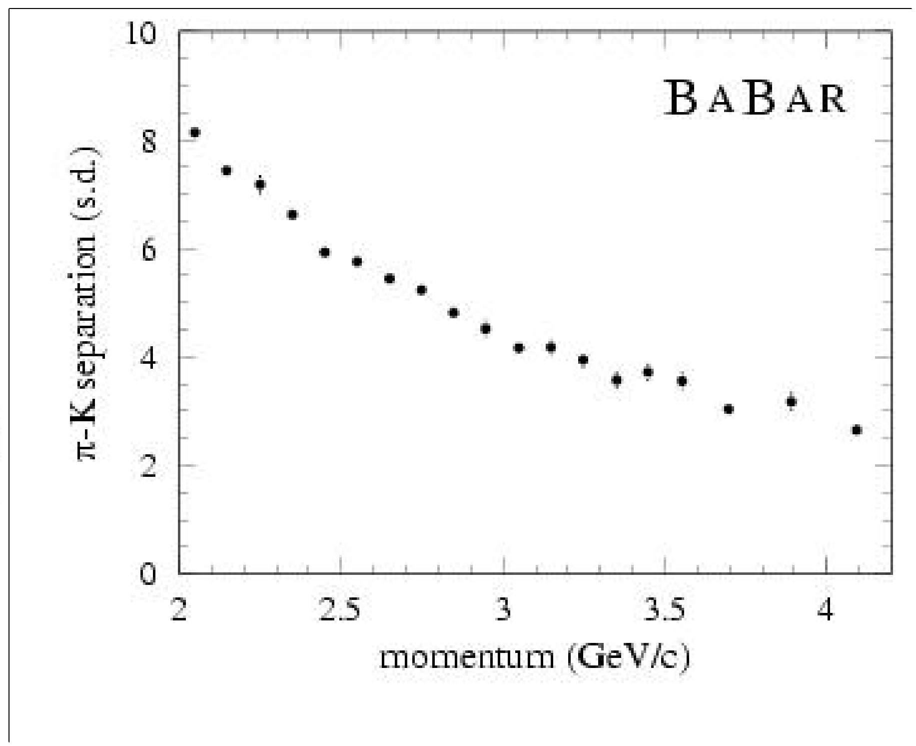
- Branching fractions ~10^{-4}-10^{-6}
- Expectations:
  - *B* –> ππ dominated by *b* –> *u* transition
  - *B* –> Kπ dominated by gluonic penguin

Kaon-pion separation with the DIRC

- Measurement of the ***Cherenkov angle*** $\theta_c = \cos^{-1}(1/\beta n)$
- Kaon threshold ~500 MeV/*c*



K–π separation in σ



Direct *CP* violation

- Conceptually, one of the simplest ways to study *CP* violation is to compare the decay rates $\Gamma(P \to f)$ and $\Gamma(\bar{P} \to \bar{f})$. Measure asymmetry:

$$A = \frac{\Gamma(P \to f) - \Gamma(\bar{P} \to \bar{f})}{\Gamma(P \to f) + \Gamma(\bar{P} \to \bar{f})}$$

- This type of *CP* violation can be observed only if there are *both CP*-violating *and CP*-conserving phases.
  - E.g., in $B \to K\pi$, there are tree and penguin contributions

Mode	Asymmetry $\mathcal{A}$
$\pi^+\pi^0$	$-0.02^{+0.27}_{-0.26} \pm 0.10$
$K^+\pi^0$	$0.00 \pm 0.11 \pm 0.02$
π^+K^0	$-0.17 \pm 0.10 \pm 0.02$
$K^+\overline{K}^0$	—
$\pi^0\pi^0$	—

➡ **So far, no evidence for direct *CP* violation in these decays**

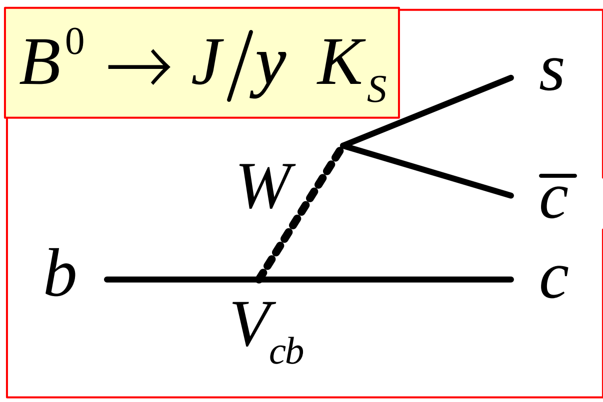
Measuring sin2α

- The decay $B^0 \to \pi^+\pi^-$ is also interesting because in principle it can be used for measuring sin2α

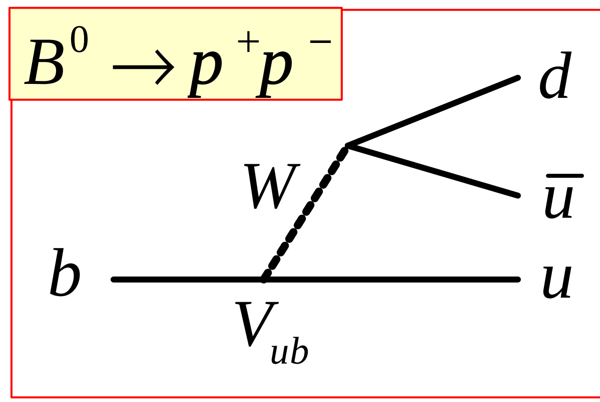
$$\frac{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) - \Gamma(B^0_{phys}(t) \to f_{CP})}{\Gamma(\bar{B}^0_{phys}(t) \to f_{CP}) + \Gamma(B^0_{phys}(t) \to f_{CP})} = S_{f_{CP}} \sin(\Delta m_d t) + C_{f_{CP}} \cos(\Delta m_d t)$$

$$S_{f_{CP}} = -\frac{2\,\mathrm{Im}\, l}{1+|l|^2} \qquad C_{f_{CP}} = \frac{1-|l|^2}{1+|l|^2} \qquad l = \frac{q}{p}\frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}$$

CKM phase appears here



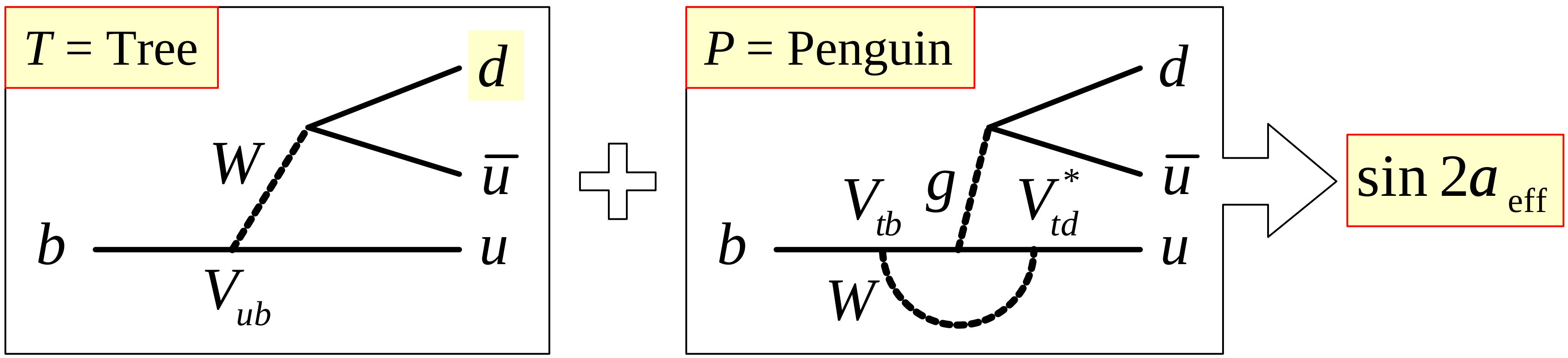
$\sin 2b$



$\sin 2a$

Why it's not quite sin2α…

- Unlike $J/y\ K_S$, p^+p^- mode suffers from significant pollution from the penguin diagrams with a different weak phase

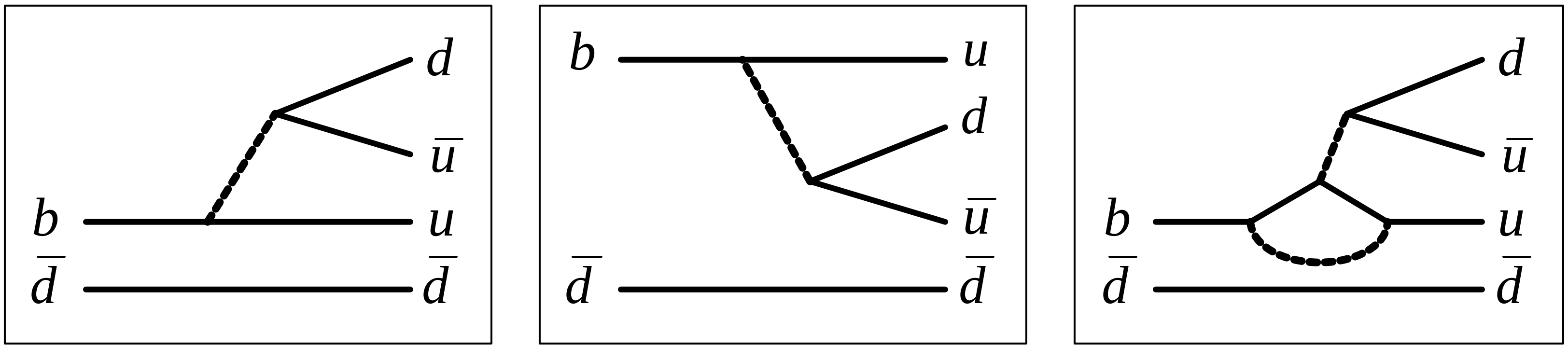


– To estimate $a_{\text{eff}} - a$, we need:
  - P/T ratio – about 1/3 from $BR(B \to Kp)/BR(B \to pp)$
  - d = strong phase difference between P and T

Taming penguins

- Take advantage of the isospin symmetry

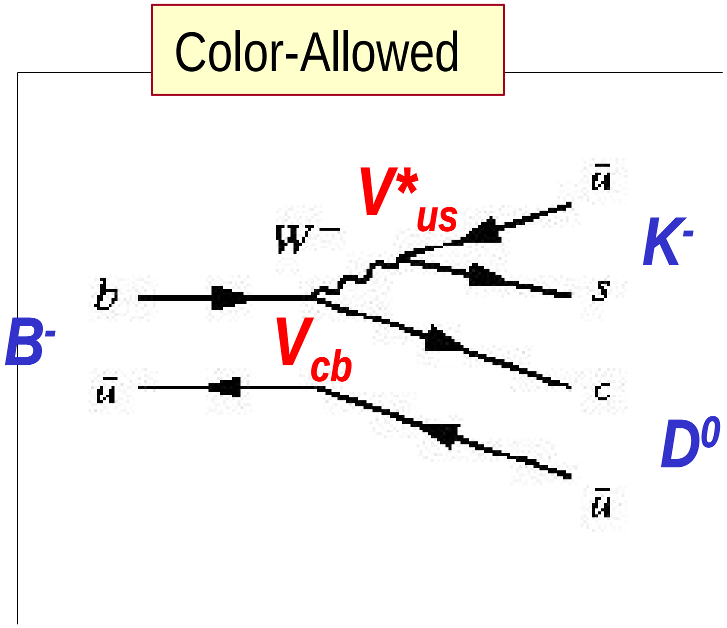
$$\mathrm{A} = a_T \cdot T + a_C \cdot C + a_P \cdot P$$

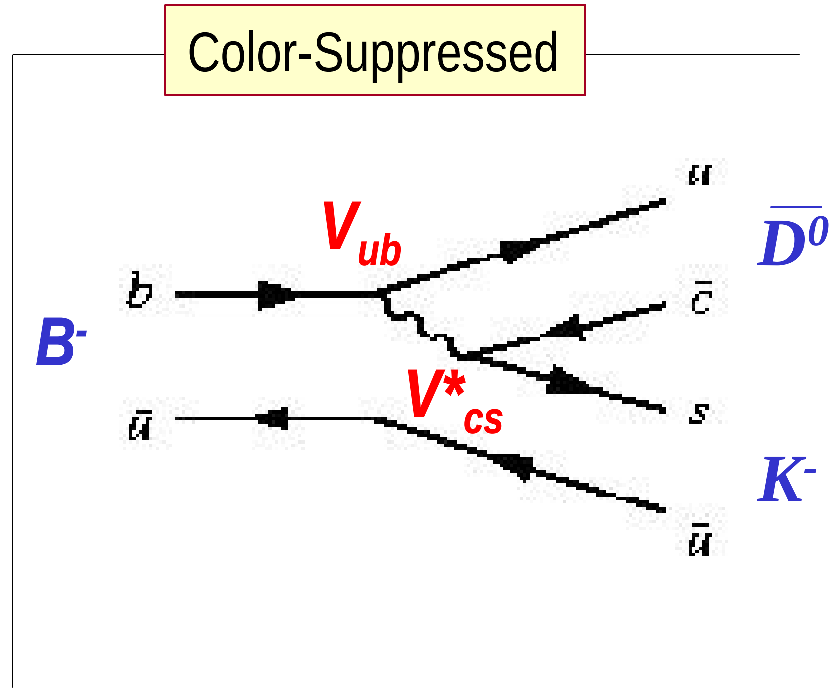


Mode	α_T	α_C	α_P	BABAR $BR{\times}10^6$	Belle $BR{\times}10^6$
$B^0 \to p^+ p^-$	$\sqrt{2}$	0	$\sqrt{2}$	$5.4 \pm 0.7 \pm 0.5$	$5.1 \pm 1.1 \pm 0.4$
$B^+ \to p^+ p^0$	1	1	0	$4.1^{+1.1}_{-1.0} \pm 0.8$	$7.0 \pm 2.2 \pm 0.8$
$B^0 \to p^0 p^0$	0	1	-1	< 3.3	< 5.6

All preliminary

Measuring γ with $B^{-} \rightarrow D^0 K^{-}$

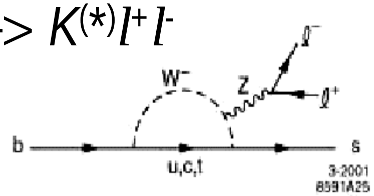


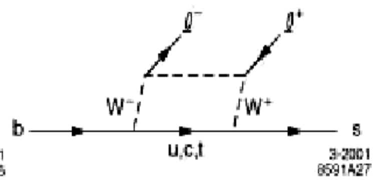


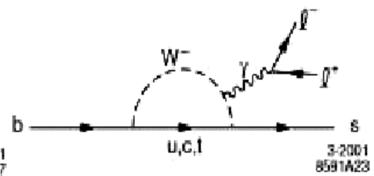
- Experimentally difficult:
  - Decay diagram suppressed by a factor 10 with respect to the favored B^{-} ® D^0 p^{-} :
    - DIRC is very important for distinguishing between the two decay modes!
  - D^0 CP decay modes are **Cabibbo suppressed** and have small branching fractions, so need a **large data sample**.

Rare radiative processes

- Rare *B* decays that can only proceed via loop diagrams in the Standard Model are sensitive to **new physics**
  - New, heavy, supersymmetric particles can appear in the loops!
  - *B* –> $K^{(*)}l^+l^-$

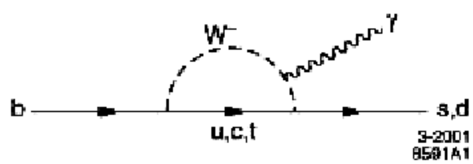






$$Br(B \to K l^+ l^-) < 0.5 \times 10^{-6} \text{ (90\% C.L.)}$$
$$Br(B \to K^* l^+ l^-) < 2.9 \times 10^{-6} \text{ (90\% C.L.)}$$

  - *B* –> *K**γ (ργ)

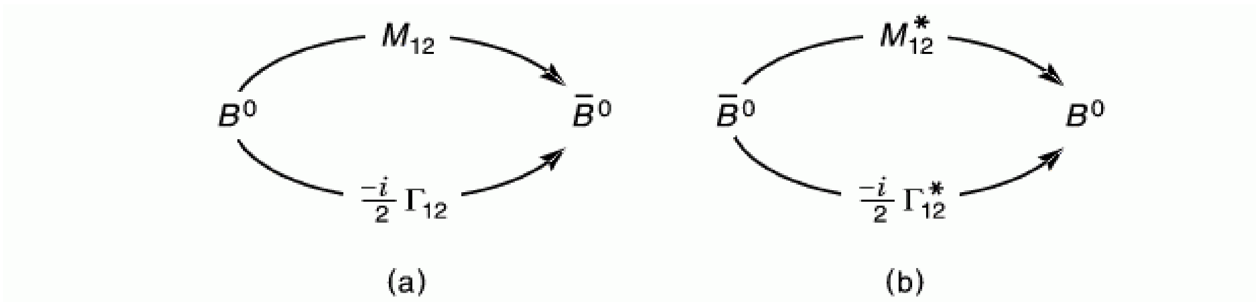


$$-0.170 < A_{CP}(B \to K^* g) < 0.082 \text{ (90\% C.L.)}$$

$$Br(B^0 \to r^0 g) < 1.5 \times 10^{-6} \text{ (90\% C.L.)}$$
$$Br(B^+ \to r^+ g^-) < 2.8 \times 10^{-6} \text{ (90\% C.L.)}$$

So far, no sign of new physics -- but need to keep looking with more data!

Mixing

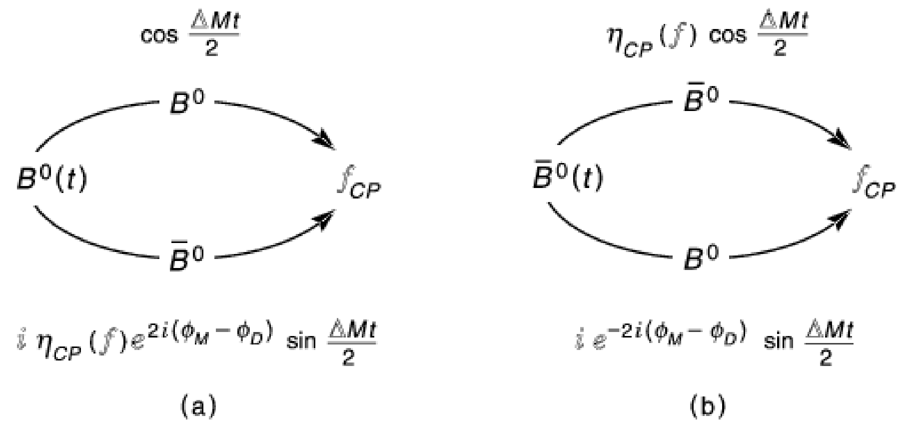


- Mixing between a pseudoscalar meson P^0 and its antiparticle can be described in terms of an effective hamiltonian matrix:

$$\mathbf{H} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

- Diagonalizing **H** gives mass eigenstates as linear combinations of P^0 and $\bar{P}^0$
- Γ_{12} describes $\bar{P}^0 \to f \to P^0$ via **on-shell** intermediate states
- M_{12} describes $\bar{P}^0 \to f \to P^0$ via **off-shell** intermediate states
- *CP* violation in mixing can arise from interference between on-shell and off-shell amplitudes
- In the *B* system, Γ_{12} is small; mixing is dominated by ΔM
  - In B_s system, Γ_{12} is large because both B_s and $\bar{B}_s$ can decay into Cabibbo-flavored states

CP Violation in Neutral *B* Decays



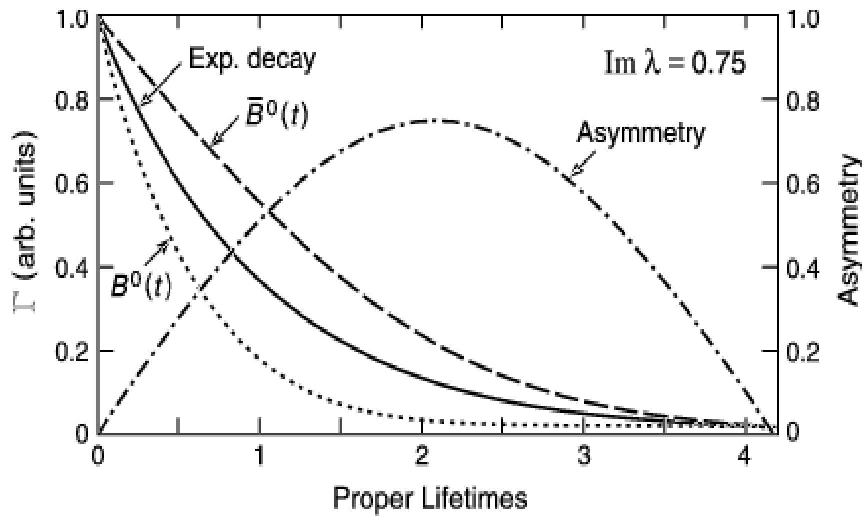
- $B^0\bar{B}^0$ mixing is dominated by off-shell intermediate states; gives a single weak phase
- To measure *CP* asymmetry, need common final state. Measure

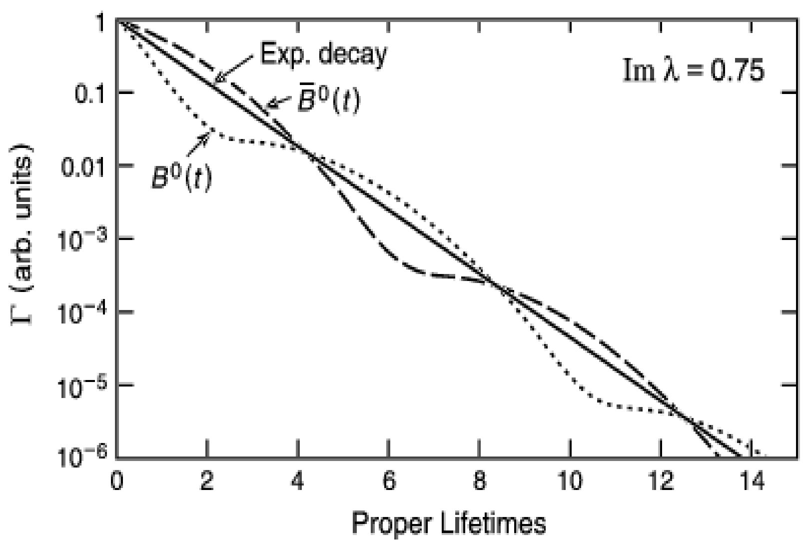
$$\boxed{A_{f_{CP}}(t) = \frac{\Gamma(B^0(t)\to f) - \Gamma(\bar{B}^0(t)\to f)}{\Gamma(B^0(t)\to f) + \Gamma(\bar{B}^0(t)\to f)}}$$

- Although *CP* asymmetries are large, useful modes (*e.g.*, $B^0 \to J/\psi\, K_s^0$) have relatively small branching fractions. Need very large data samples: 30 M to 50 M $B\bar{B}$ events or more. For $B^0 \to J/\psi\, K_s^0$

$$\boxed{A_{f_{CP}}(t) = -\sin 2b\, \sin(\Delta M t)}$$

Specifics for Υ(4S)

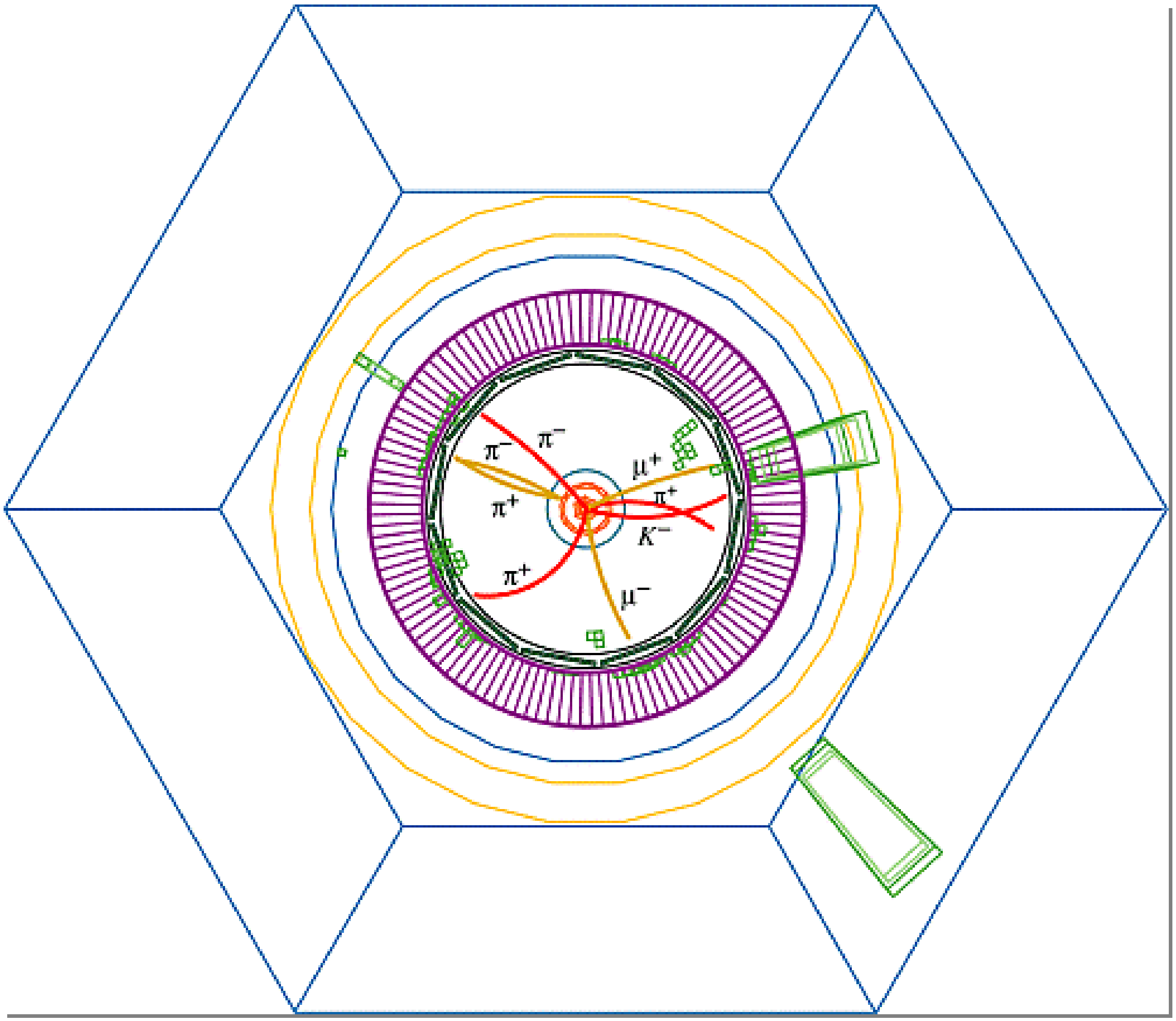




- Due to correlated time evolution in Υ(4S) –> $B^0\overline{B}^0$, the asymmetry reverses sign when t_{CP} - t_{tag} reverses sign. This forces the time-integrated asymmetry to vanish. So we must measure time-dependent *CP* asymmetry => vertexing is critical!
- Tagging of initial state: use lepton and kaon from other *B* meson

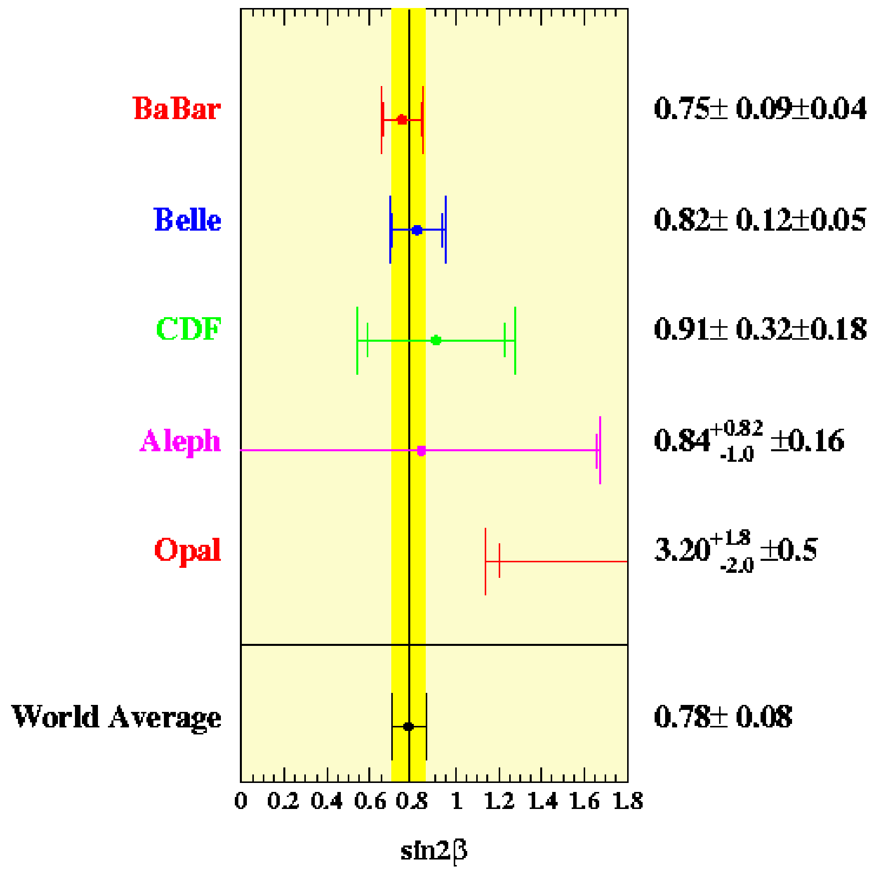
  $b \to l^-$, $b \to c \to s$
- Need excellent particle ID: e,μ, K, π, both for tagging and reconstruction of *CP* final state
- The mode $B^0 \to J/\psi\, K_s^0$ is a "golden mode" because of its theoretical simplicity and strong experimental signature.

One of BaBar's "Golden Events"



BaBar's Current Measurement of sin2β

$\sin 2\beta = 0.75 \pm 0.09\ (\mathrm{stat}) \pm 0.04\ (\mathrm{sys})$



The sin2β measurement does not indicate new physics

Conclusions and Prospects

- Leptonic decays are barely seen (D_s only)
- We are just beginning to map out $b \to u l \nu$, to understand their dynamics, and to measure $|V_{ub}|$
- Hadronic rare decays are being explored. It's still possible to observe direct *CP* violation in such modes.
- Much remains to be learned about radiative penguin modes.
- Charm physics still has a lot to teach us. We need to continue focusing on $D^0\bar{D}^0$ mixing
- $\sin2\beta$ measurements are becoming precise. No sign of new physics found yet.
- Will see much improved measurements of $\sin2\alpha$ and $\sin2\gamma$ in the next few years